Development of Statistical Model to Predict R_a and R_z in the Laser Cutting

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Abstract

Laser cutting is one of the advances machining on material remover process. This paper explores the prediction model of surface roughness (R_a) and roughness height (R_z) of laser beam cutting on acrylic sheets. Box-Behnken design based Response Surface Method (RSM) was used to predict the effect of laser cutting parameters which are laser power, cutting speed and tip distance on R_a and R_z. The predictive models are good agreement with experimental results. The first order equation revealed that the power requirement was the dominant factor followed by tip distance and cutting speed respectively. This observation indicates that the potential of using RSM in predicting cutting parameters thus eliminating the need for exhaustive cutting experiments to obtain the optimum cutting condition and enhance the surface roughness.

Keywords: Laser beam cutting, Box-Behnken design, surface roughness, acrylic sheets, surface height

1 Introduction

Laser light differs from ordinary light due to it has the photons of same frequency, wavelength and phase. Thus, unlike ordinary light laser beams are high directional, have high power density and better focusing characteristics [1, 2]. These unique characteristics of laser beam are useful in processing of materials. The laser beams are widely used for machining and other manufacturing processes such as cutting, drilling, micromachining, marking, welding, sintering and heat treatment. Lear beam machining (LBM) is a thermal energy based advanced machining process in which the material is removed by melting, vaporization and chemical degradation.

According to Powel [3] and Rooks [4] applications of laser cutting in polymeric materials have grown considerably in many industries. Polymeric materials generally fall into main groups. There are thermoplastics, such as polyethylene (PE), polycarbonate (PC), polymethylmethacrylate (PMMA) (acrylic), polyvinylchloride (PVC) and thermoset plastics, which include epoxy and phenolic resins. Rooks [4], Caiazzo *et al.* [5], Zhou and Mahdavian [6], Mathew et al. [7] and Lum *et al.* [8] when reporting on laser cutting of polymeric materials, have shown that the processing parameters have an essential role on the quality of the surface obtained. Lum *et al.* [8] presented a study about the CO2 laser cutting of medium-density fibreboard (MDF). This work reports on the determination of processing parameters setting for the effective cutting of MDF by CO2 laser, using an established experimental methodology developed to study the effects of varying laser set-up parameters. According these authors striation patterning is evident but is of little significance to the overall quality of cut as evidenced by the low roughness values obtained. Recent study by Davim et al. [9] the experiences in CO2 laser cutting of polymers/composites, it is evident that the HAZ increases with the laser power and decrease with the cutting velocity.

When a high energy density laser beam is focused on work surface the thermal energy is absorbed which heats and transforms the work volume into a molten, vaporized and chemically changed state that can be easily be removed by flow of high pressure assist gas. LBM can be applied to a wide range of materials such as metals and non-metals. Laser surface texturing may be an ideal technology for applications in mechanical face seal, as well as in various components in engine such as piston ring and cylinder and thrust bearings, involving creation of an array of micro dimples or channels artificially distributed on the mating surface with a pulsed laser beam [10-11]. With the development of laser technology and flat panel display (FPD) technology, many studies have been carried out to investigate the methods of cutting glass using lasers [1,2,12–20]. Li et al. [10] put forward a mathematical model to explain the heat transfer of glass heated by lasers and to analyze the differences of the effect on the thermal behaviour of glass between the application of lasers as a volumetric heating source and that of a surface heating source. Wei [11] and Tian [13] investigated the thermal behaviour of glass heated by a CO2-laser beam numerically, and concluded that the resulting temperature distribution was strongly dependent on the speed of the moving laser beam and the laser parameters, i.e., the size of laser beam and the power of the laser. Tsai et al. [14] studied the thermal stress of alumina ceramic substrates irradiated by a moving laser beam. R_z is the arithmetic mean value of the single roughness depths of consecutive sampling lengths. Z is the sum of the height of the highest peaks and the lowest valley depth within a sampling length.

In any manufacturing process it is always desired to know that the effect of variation of input parameters on process performance in order to achieve the goal of better product quality. LBM being a non-conventional machining process requires high intensity and offers poor efficiency. Therefore, high attention is required for better utilization of resources. The values of process parameters are determined to yield the desired product quality and also to maximize the process performance. In LBM, there are various variables including beam power, cutting speed and tip distance which affect the surface roughness. Surface roughness value reduces on increasing cutting speed and frequency, and decreasing the laser power and gas pressure. Also nitrogen gives better surface finish than oxygen [15]. The laser power and cutting speed has a major effect on surface roughness as well as striation frequency [16]. From the above review, it can be concluded that, in the past, there are very few papers reported on the relationship of variables and response when machining acrylic sheets. This paper emphasis on the development of surface roughness and surface height models in machining with laser beam and discusses the relationship of the variables with response.

2 Response Surface Method

RSM is a collection of statistical and mathematical methods that are useful for the modelling and optimization of the engineering problems. In this technique, the main objective is to optimize the responses that are influencing by various parameters. RSM also quantifies the relationship between the controllable parameters and the obtained response. In modelling of the manufacturing processes using RSM, the sufficient data is collected through designed experimentation. In general, a second order regression model is developed because of first order models often give lack-off fit [17]. The study uses the Box-Behnken design in the optimization of experiments using RSM to understand the effect of important parameters. Box-Behnken design is normally used when performing a non-sequential experiment which is performing the experiment only once. These designs allow efficient estimation of the first and second – order coefficients. Box-Behnken design has less design points; it's less expensive to run than central composite designs with the same number of factors. Box-Behnken Design does not have axial points, thus it can be sure all the design points fall within the safe operating. Box-Behnken design also ensures that all factors are not being set at their high levels simultaneously [18-20].

3 Experimental Set-Up

The experiment was performed on a 30W pulsed CO_2 laser beam system with CNC work table. The oxygen was used as an assist gas. The variable process parameters taken are: beam power, cutting speed and tip distance. Focal length of the lens used is 50 mm, 1.0 mm nozzle diameter and 1.0 mm nozzle tip distance, were kept constant throughout the experiments. The fifteen experiments are carried out using the laser machine, as shown in Fig. 1. Acrylic sheet of the 3.0 mm thickness, 30.0 mm width and 40.0 mm long was taken as the specimen and was cut into rectangular shape in order to measure the surface roughness.

The dimension of acrylic sheet specimen is shown in Fig 2. Four sides were measured to get the average roughness. Surface roughness tester Perthometer S2 was used for the roughness measurement. The material properties of the workpiece are shown in Table 1. The suitable levels of the factors were used in the statistical Minitab software to deduce the design parameters for acrylic sheets, which is given in Table 2. The lower and higher speed values were selected of 700 pulses/s and 1100 pulse/s respectively. The higher and lower values of power requirement of 95% and 90% are considered. The range of tip distance is 3 mm to 9 mm.

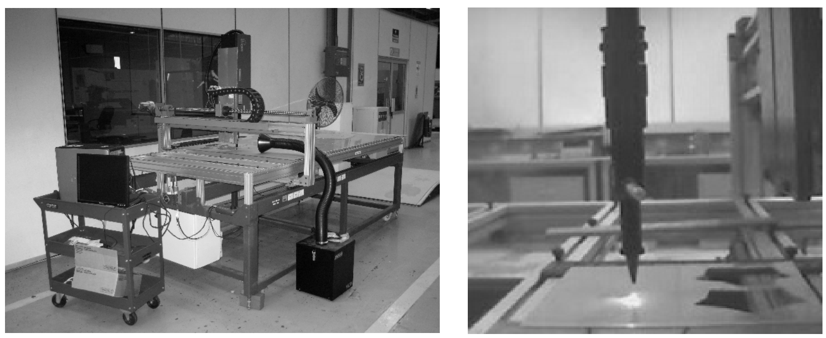

Figure 1: Laser machine

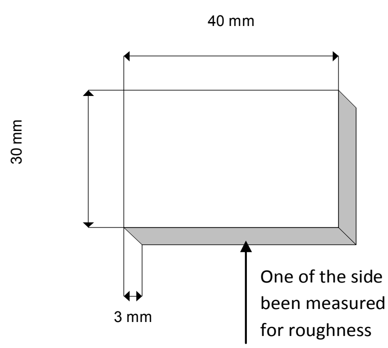

Figure 2: Dimensions of the specimen

Table 1: Material properties of specimen

Properties	Value	Unit
Density	1170	kg/m^3
Yield Tensile Strength	52.1	MPa
Processing temperature	156	°C
Modulus of elasticity	2.31	GPa

Table 2: Level of design variables

Design Variables	Coding of levels		
	1(lowest)	0(middle)	1(highest)
Power requirement (%)	90	92.5	95
Cutting speed (pulse/s)	700	900	1100
Tip distance (mm)	3	6	9

4 Results and Discussion

After 15 cutting experiments were conducted, the surface roughness's readings are used to predict the parameters appear in the postulated first order model, which were expressed as Eq. (1) and (2) respectively. In order to calculate these parameters, the least square method was used to determine these parameters with the help of statistical software. Linear equation used to predict the surface roughness and surface height, which are expressed as Eq. (1) and (2).

$$R_a^{(1)} = -0.7059 + 0.0124\,\mathrm{Pr} - 0.0000265 C_{speed} + 0.016 GD \tag{1}$$

$$R_z^{(1)} = -0.4899 + 0.02695\,\mathrm{Pr} - 0.000485 C_{speed} + 0.1372 GD \tag{2}$$

where R_a is surface roughness, R_z is surface height, *Pr* is the power requirement, C_{speed} is cutting speed and *TD* is the tip distance.

From this linear equation, the response surface roughness and surface height are affected significantly by the power requirement, followed by tip distance and cutting speed. Eq. (1) and (2) shows that combination of high power and tip distance produce a rough surface. On other hand, high cutting speed produces a very smooth surface. Similar to the first-order model, by examining the coefficients of the first-order terms, the tip distance (*TD*) has the most dominant effect on the surface roughness. The contribution of power requirement (*Pr)* is the least significant. The ANOVA analysis shown in Tables 3 and 4, indicate that the model is adequate as the P-value of the lack-of-fit is not significant (> 0.05). Fig. 4 and 5 show the contour plot for R_a and R_z. One easily can observe the relationship between variables and response.

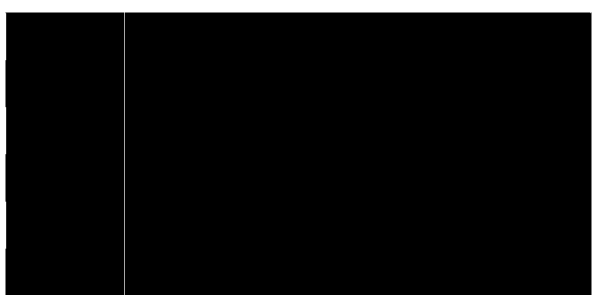

Figure 3: Prediction value of predicted value by RSM for R_a and R_z

Table 3: Analysis of variance (ANOVA) for first-order equation R_a

Source of variation	Degree of freedom	Sum of squares	*F*-ratio	*P*-value
Regression	3	0.02676	0.09	0.964
Linear	3	0.02676	0.09	0.964
Residual Error	11	1.09008		
Lack-of-Fit	9	0.992	2.25	0.346
Pure Error	2	0.09808		
Total	14	1.11684		

Table 4: Analysis of variance (ANOVA) for first-order equation R_z

Source of variation	Degree of freedom	Sum of squares	*F*-ratio	*P*-value
Regression	3	1.47441	36.82	0
Linear	3	1.47441	36.82	0
Residual Error	11	0.14682		
Lack-of-Fit	9	0.10291	0.52	0.798
Pure Error	2	0.04391		
Total	14	1.62123		

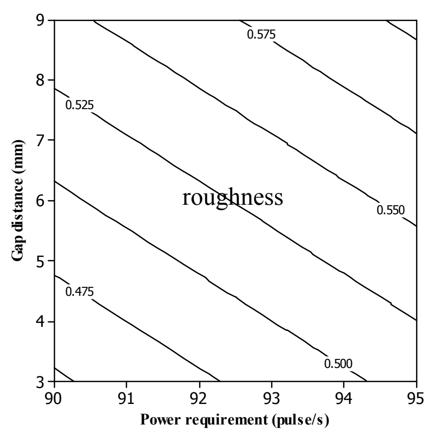

Figure 4: Surface roughness contours in the power requirement-gap distance plane for (a) cutting speed 900 pulses/sv

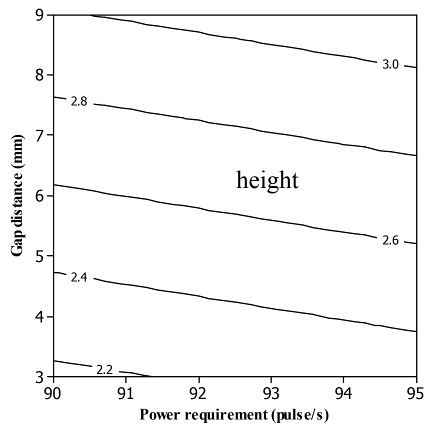

Figure 5: Surface height contours in the power requirement-gap distance plane for (a) cutting speed 900 pulses /s

5 Conclusions

In the current work, the response surface methodology has been proven to be a successful technique to perform the trend analysis of surface roughness and surface height with respect to various combinations of three design variables. By using the least square method, the first-order models have been developed based on the test conditions in accordance with the Box–Behnken design method. The models have been found to accurately representing the surface roughness and surface height values with respect to those experiment values. The equations have been checked for their adequacy with a confidence interval of 95%. Both models reveal that the power requirement and tip distance is the most significant design variable in determining the surface roughness response as compared to the others. In general, within the working range of the power requirement and tip distance considered the surface roughness and surface height increases as the both variables increases. The models have been found to be accurately representing surface roughness values with respect to experimental results. RSM model reveal that power requirement is the most significant design variable in determining surface roughness and surface height response as compared to cutting speed and tip distance. With the model equations obtained, a designer can subsequently select the best combination of design variables for achieving optimum surface roughness. This eventually–reduces the machining time and save the cutting tools.

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